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MEASUREMENTS OF UNDERWATER EXPLOSIVE SOURCE LEVELS FOR YIELDS OF 0.0012 TO 126 POUNDS

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General Motors Corporation

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Submitted to
DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
UNDERSEA PROGRAMS BRANCH
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Sea Operations Department

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13 ABSTRACT

The equivalence of using energy measurements for explosives and intensity for CW sources in the determination of underwater acoustic transmission loss has been previously investigated by Hasse and Stockhausen for one-pound TNT charges. It was concluded that use of Weston's theoretically derived energy source levels was satisfactory for this size charge. The objective of the present experiment was to investigate the applicability of Weston's predictions of energy source level for a broader range of charge yields in view of estimates by Arons and others that the range at which an explosive signal propagates as an acoustic wave is critically dependent on charge yield. Shot energy source levels were determined by measuring received signal energy and then adding transmission loss values for the path which were measured using a constant wave projector. It was found that, within the accuracy limits of the experiment, Weston's "sum" formula is a close representation of the true energy source level of explosives in the yield range of 0.0012 to 126 pounds TNT above a frequency equal to about the first bubble pulse frequency and is therefore usable for transmission loss determinations. Suitable averaging of the signal over frequency is necessary because of the bubble pulse frequency harmonic-related uneveness of the explosive source spectra. Also, because of fluctuation in the transmission path, a sufficient number of charges must be used to sample in a statistically significant manner depending on the degree of fluctuation observed. To a close approximation, at frequencies below the first bubble pulse frequency, the energy source level has a 7 dB/octave slope. Weston's prediction of critical depth (above which his predictions could be in error due to bubble migration effects) appears to be too conservative. Considerably shallower charges used in the experiment indicated no repeatable trends of variance from his source level prediction.

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Illustrations

Measurements of Underwater Explosive Energy Source Levels for Yields 0.0012 to 126 Pounds

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GENERAL

Explosives have proven to be convenient, economical sources for obtaining acoustic transmission loss data in the ocean. The high intensity impulses from the shock wave and bubble pulses produce considerable amounts of energy over a very broad frequency spectrum. Thus, through a single recording of their signals, they provide a means for obtaining transmission loss across a wide band of frequencies. Explosives are particularly useful in the study of long-range propagation in the Arctic where only low-frequency energy propagates with efficiency, and the size and weight of low-frequency sonic projectors pose critical deployment problems. In order to gain high source energy at these low frequencies and at depths to over 1000 feet, explosives of up to 300 pounds have been employed in that area.

The standard technique[1] of transmission loss measurement has been to measure the energy flux density of the received signal by squaring and integrating the acoustic pressure, and subtracting this from the calculated or measured energy flux density at some reference range near the source.

Measurements near the source are not always possible and, in any case, are difficult because of instrumentation saturation on the high amplitude impulses generated by the explosion. Usually, the source energy is calculated for a reference range of 100 yards by using formulas developed by Weston[2] and then the 1-yard reference is attained by adding 40 dB to account for assumed spherical spreading. However, the equivalency of this procedure to loss measurements made with continuous-wave or pulsed sinusoidal signals has been questioned because measurements of peak pressures of the shock wave at close range have indicated a different decay rate than relatively small amplitude acoustic waves.

Arons[3] has stated that an explosive signal does not propagate as an acoustic wave until it reaches a range of 10^4 to 10^5 times the charge radius. R. Plutchok* (personal communication) analyzed the relative amplitudes of the shockwave and first bubble pulse peak pressures at various ranges from small charges exploded at deep depths by using data published by Blaik and Christian[4] and concluded that the range beyond which the ratio of the two amplitudes remained essentially constant was about $W^{1/3}10^4$ (feet), where W is the yield in pounds of TNT. Both Arons' and Plutchok's estimations of what might be termed the "far field" of an underwater explosion are shown in Figure 1. It can be seen that, even for a charge of small yield, the range beyond which the signal can be expected to propagate as an acoustic wave is considerable. For example, Arons' lower and upper limits range from 440 yards to 4400 yards for a one pound charge. Depending on the magnitude of this effect within the near field, considerable errors in measured transmis-

*ENSCO, Inc.

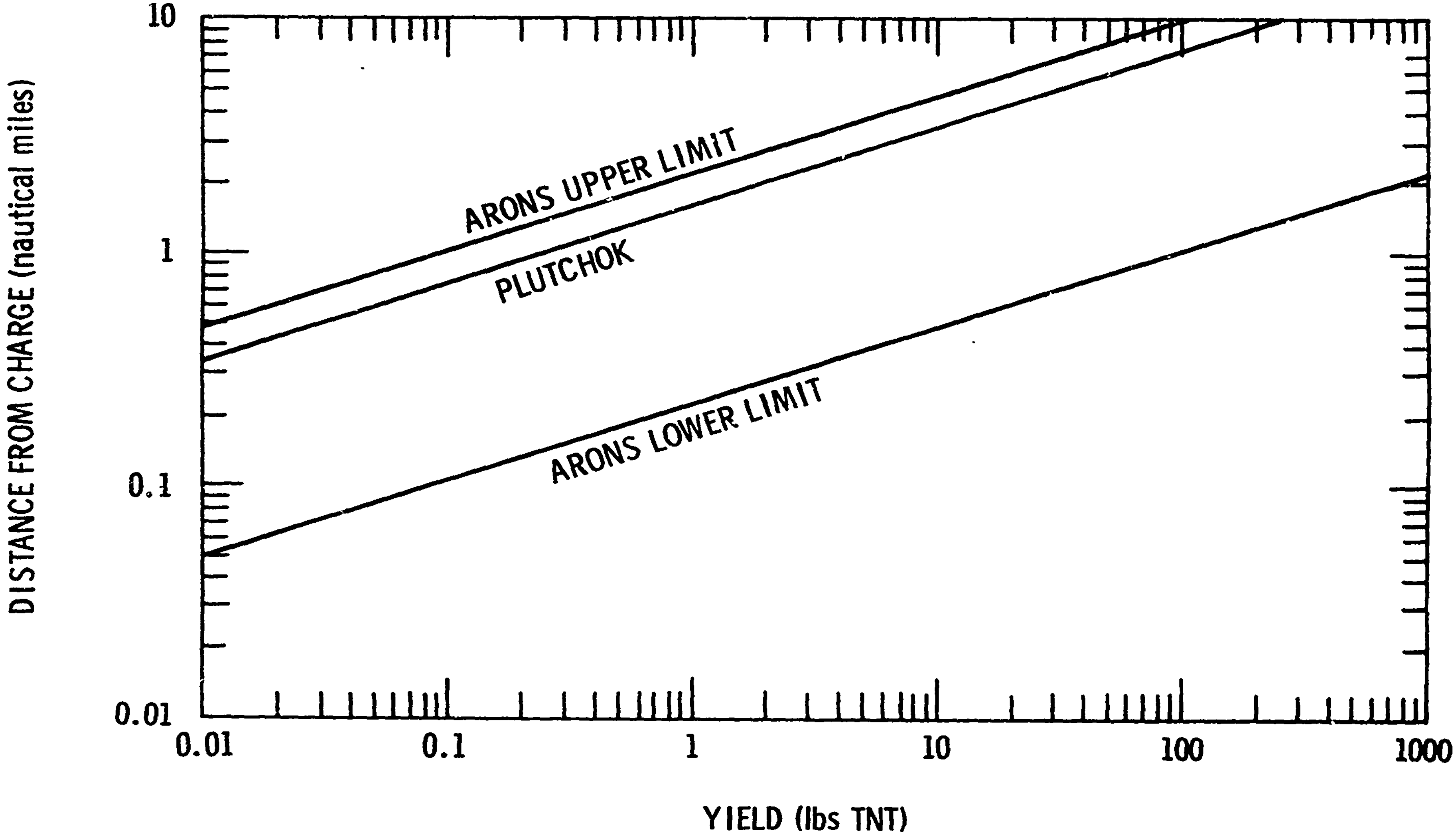

Figure 1. Estimation of Extent of Near Field from Explosives

sion loss could be experienced, especially for large charges.

This concern is not new. In 1960, R. W. Hasse, Jr.[5] reported on comparisons of propagation loss measurements made by using explosives and sinusoidal signals. His measurements covered three frequencies (354, 562 and 1120 Hz) and ranges between 1 and 35 miles. He concluded that the observed difference in propagation loss between the two types of signals was less than 3 dB and even this much difference probably was due to sample size, long-term fluctuations in the medium and measurement precision. In 1964, Stockhausen[6] reported measurements made of the energy flux density spectrum level of the shock wave 100 yards from charges exploded at a depth of 120 feet and concluded that over the frequency range 100-25,000 Hz, the measurements were in agreement with values calculated. Both of these prior experiments were with one-pound TNT charges and no data could be found in the literature to indicate that larger charges had been similarly investigated. Yet, according to Arons[3], the larger the charge the greater the possible error in transmission loss due to the extension of the far field (Figure 1).

Shortly after the experiment described herein was conducted, a similar experiment was reported by Kibblewhite and Denham[7] in which the aim was to investigate the variations in source level with charge weight, frequency and depth, and to compare the results with Christian's[8] predictions.

A recent report by Gaspin and Shuler[9] indicated the fallacy of attaining source levels of shallow explosives by the method of time-pressure measurements because of surface reflection contamination. They derived an "idealized" source level that is significantly different from Weston's.

As Weston correctly points out, the variation of charge-source level with depth is obviously of interest, especially for long-range transmission loss measurements at low frequency. He recognized the possibility that bubble migration effects for shallow charges could influence his predictions of source energy. He calculated the "critical depth" at which such effect become small as:

$$d_o = 200W^{1/4} \text{ feet} \tag{1}$$

A plot of Equation 1 and the average yields of the types of explosives used during this experiment are shown in Figure 2.

DESCRIPTION OF EXPERIMENT

It has been mentioned that explosives are convenient sources for Arctic propagation experiments. The converse is also true: the Arctic is a convenient place to measure characteristics of explosives. The ice cover provides a stable platform from which charges can easily be deployed and the water currents below the ice are usually very small. The Arctic water sound velocity profiles are relatively stable and ambient noise levels are at times much lower than in open-ocean areas. For these reasons, it was possible to conduct the experiments described below with three men in a few days and in conjunction with long-range propagation tests in the Arctic. The tests were conducted at the floe station ARLIS 5 (Arctic Research Laboratory Ice Station Number 5) located in the vicinity of 73°20'N, 156°W in water about 10,000 feet deep during April 1970.

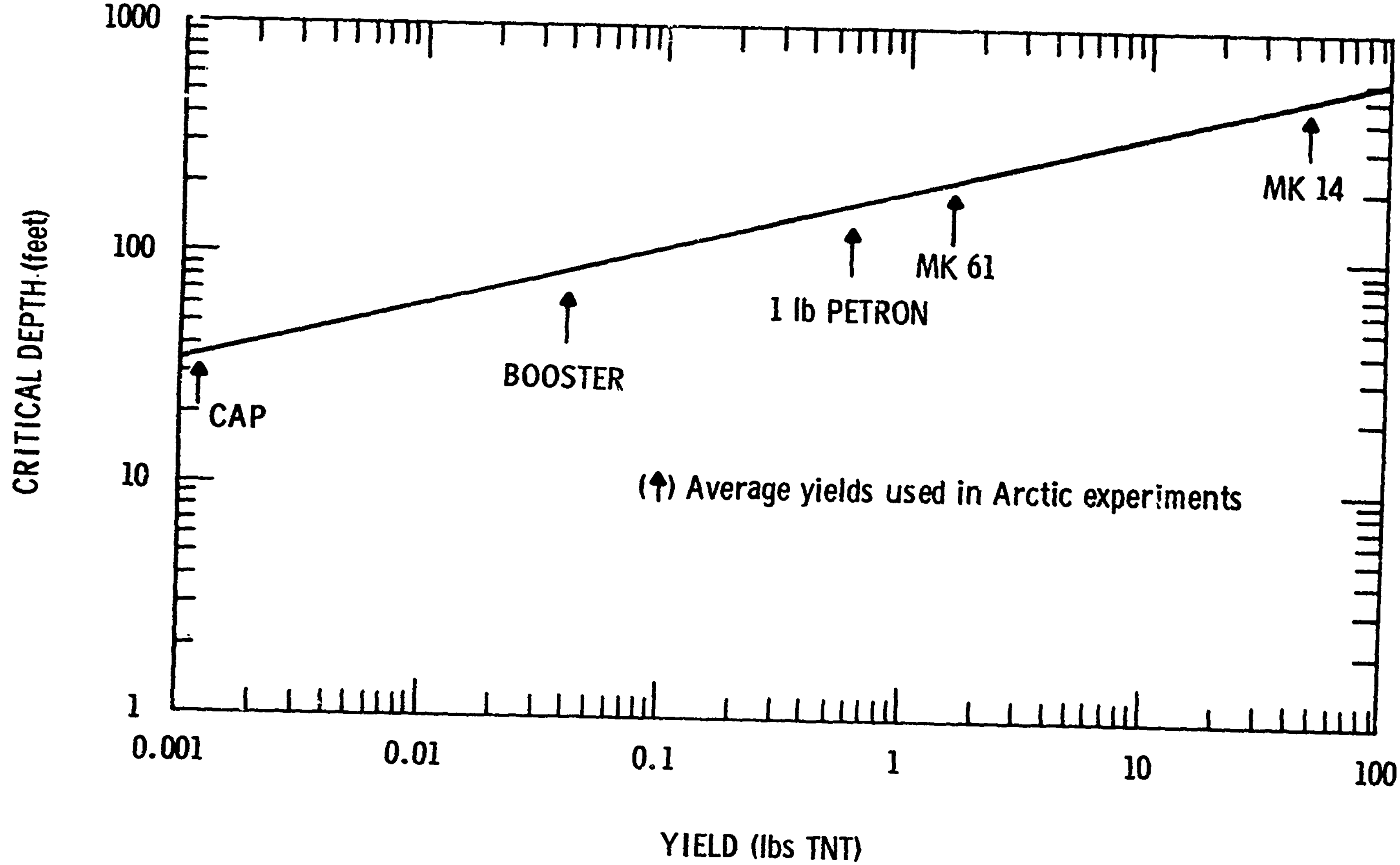

Figure 2. Weston's Critical Depths for Bubble Migration Effects

The objective of the experiment was a measurement of source level energy of charges of various sizes and at depths that would enable a comparison with Weston's predictions, and to determine if long-range transmission loss (measured by subtracting received energy flux density from those predictions) could be expected to yield the same results as projections of continuous-wave sinusoidal signals. Explosives of various sizes from blasting caps to block TNT charges of 126 pounds were detonated at various depths at two satellite stations, 1.2 and 2.3 nautical miles from ARLIS 5. Signals were received by using a 100-foot hydrophone (USN USRD standard hydrophone Type F36). The received signals were filtered in the fixed bands described in Table I and then squared and integrated to yield received energy flux density in each band.

An automatic "saturation detector" circuit was employed at the input to the tape recorder at ARLIS 5 to indicate when shot signal levels were high enough to saturate the FM tape recorder electronics. When this occurred, a calibrated attenuator on the F36 hydrophone output was increased and the particular shot repeated, thereby assuring that no saturated data were used in the later analysis.

After receiving a shot series, the transmission loss over the path was measured by using a Type J-11 projector located at the F36 receiving hydrophone and projecting the CW signal to a second hydrophone which had been lowered to the exact depth of the shot series. Three CW signals were projected in each of the analysis bands of Table I for periods of 2 to 5 minutes; the received signal levels were averaged to obtain transmission loss

Table I

ANALYSIS FILTER CENTER FREQUENCIES AND BAND LIMITS

(The filters consist of two 4-pole Butterworth filters in series)

Band	Center Frequency (Hz)	Band Limits (Hz)
1	10	5-15
2	20	15-25
3	30	25-35
4	40	35-45
5	50	45-55
6	65	55-75
7	85	75-95
8	110	95-125
9	140	125-155
10	175	155-200
11	225	200-250
12	275	250-300
13	350	300-400
14	450	400-500
15	750	500-1000
16	1500	1000-2000

over the path.

By reciprocity, both paths are equivalent. This test arrangement is shown in Figure 3. Both the received shot signals and the CW signals were recorded on magnetic tape and later analyzed. Quiet periods were selected for the tests to assure high signal-to-noise ratios for the CW projections. Both receiving hydrophones were calibrated before and after the experiment at either USN USRD or TRANSDEC. Projected levels on the J-11 projector were monitored with the hydrophones one and two yards above the acoustic center of the J-11 radiating diaphragm. These monitor hydrophones were field calibrated repeatedly by using the F36 in a comparison mode on J-11 signals. The TNT equivalent yields of all explosives were obtained in the following manner. A low-gain hydrophone in the vicinity of the charges fed an oscilloscope which was set to a single-sweep trigger on the shock wave. The first bubble pulse interval was measured and yield calculated using Weston's bubble pulse formula:

$$\text{bubble pulse interval} = kW^{1/3}/(d + 33)^{5/6} \tag{2}$$

where: $k = 4.36$ for TNT

W = yield in pounds

d = shot depth in feet.

The above experimental procedure is similar to that used by Hasse[5] except where he used only three CW projection frequencies, we used 16 to define better the transfer function imposed by the medium. Surface reflection and other multipaths do not basically invalidate the procedure but they do complicate it. A more satisfactory method would have utilized broadband noise

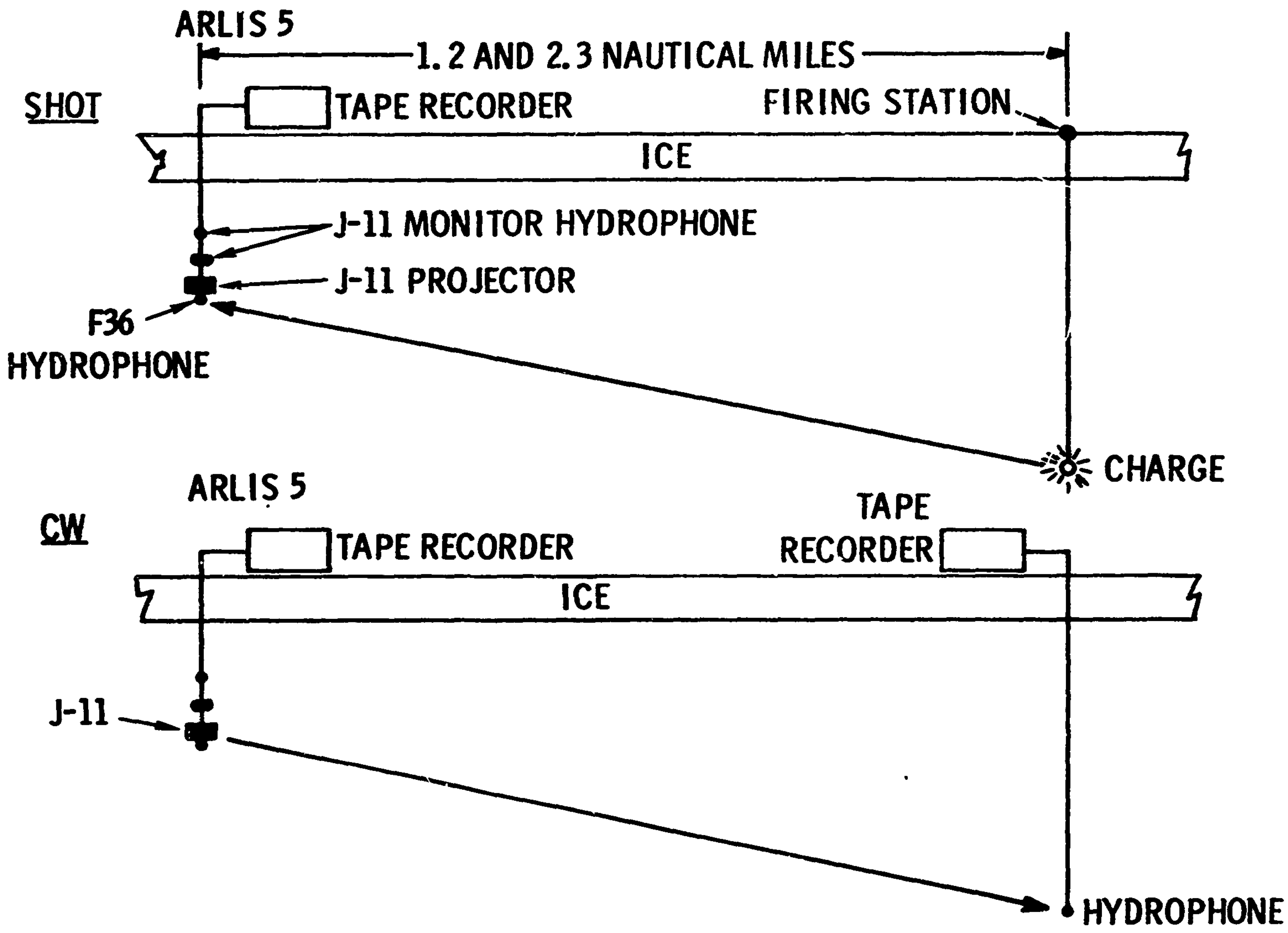

Figure 3. Test Set-Up for Determining Shot Source Levels

projection of accurately known characteristics but this was impractical because of the limited power capabilities of the J-11 projector.

WESTON VS MEASURED SOURCE ENERGY COMPARISON

The results of the short-range experiments performed in the vicinity of ARLIS 5 are shown in Figures 4 through 10. Figures 4 through 9 show Weston's "sum" (sum of the shock wave, first bubble pulse and second bubble pulse) plotted from the first bubble pulse frequency up to 500 Hz for the charge yields and depths used at ARLIS 5. Plotted in these figures are the measured energy source levels of the charges detonated at the two ARLIS 5 satellite stations. These energy source levels were obtained by adding the measured CW transmission loss for the appropriate 1.2 or 2.3 nautical mile satellite station, depth and frequency to the signal energy levels measured from the explosions. Also shown in these figures are calculated values of Weston's "critical depth".

An inspection of Figures 4 through 9 indicates no systematic trends in the differences between predicted and measured energy source levels as a function of range, yield, depth or frequency above the first bubble pulse. Neither is there any clear difference between charges detonated deeper or shallower than Weston's "critical depth". For selected single data points, there are seen to be significant differences. However, this is attributed to fluctuation in the test paths. During the CW measurements, the projector signal was observed to vary by approximately the same amount as those differences in Figures 4 through 9. This fluctuation is characteristic of short

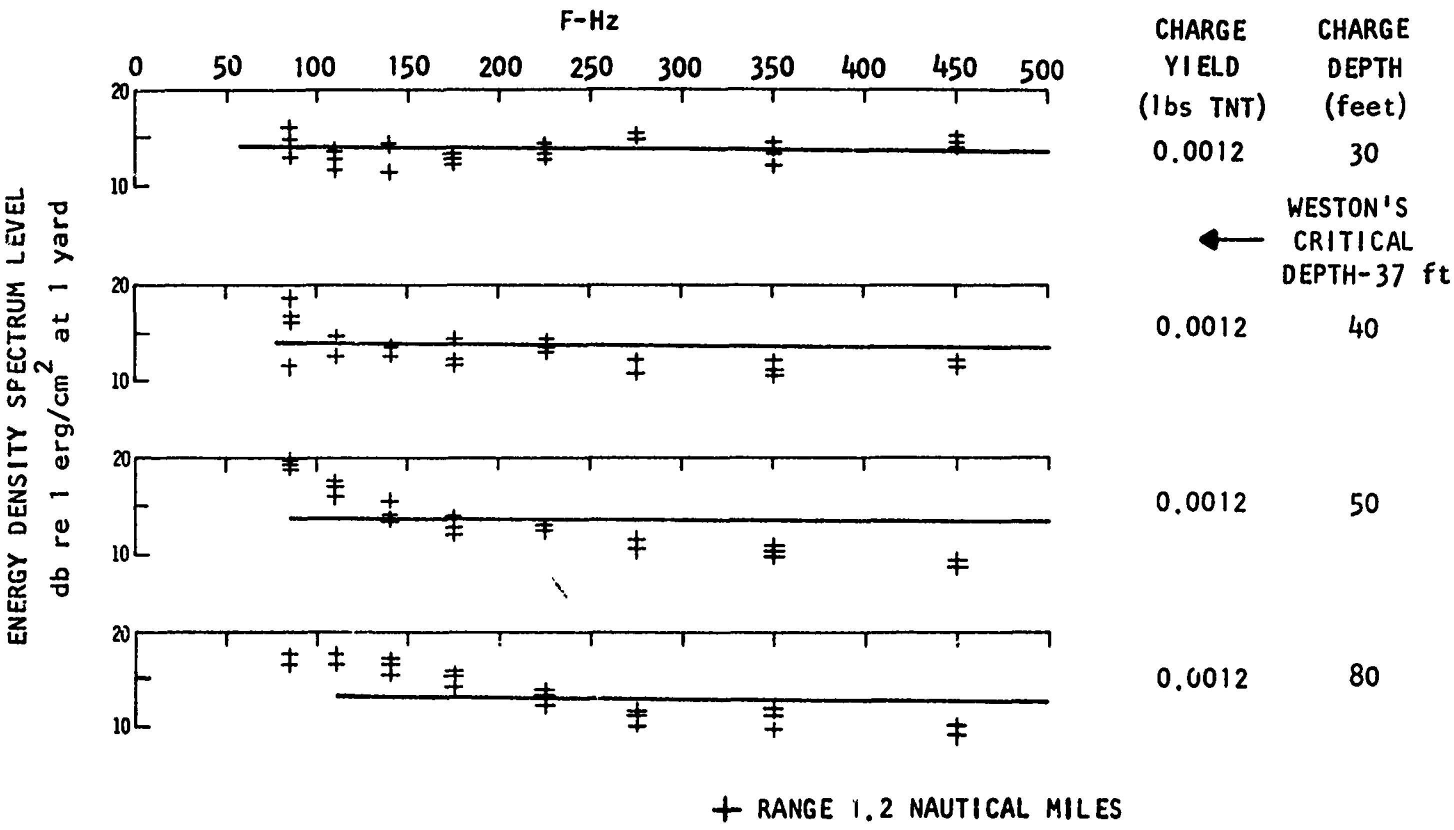

Figure 4. Measured Source Level and Weston's Predicted Source Level

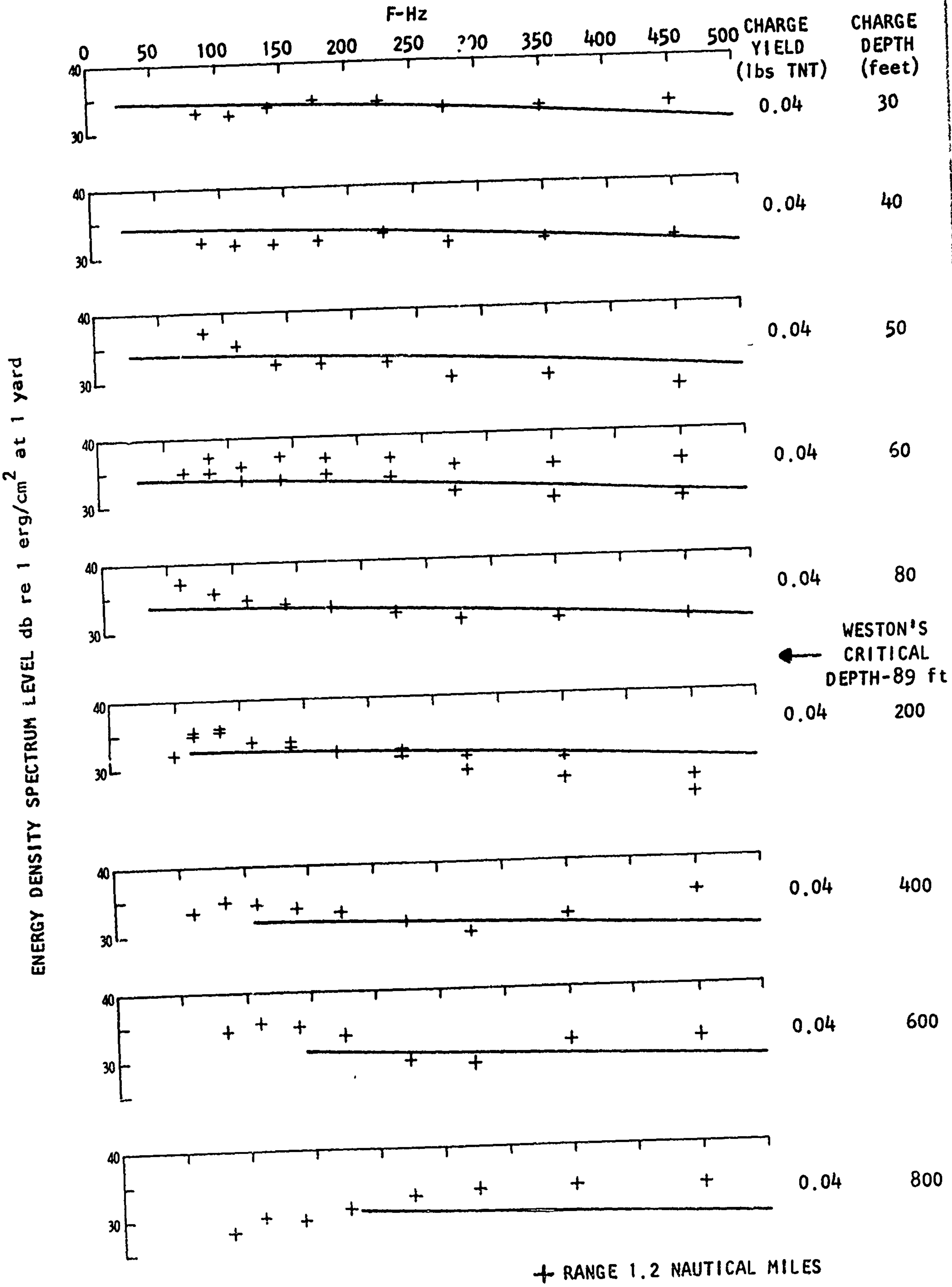

Figure 5. Measured Source Level and Weston's Predicted Source Level

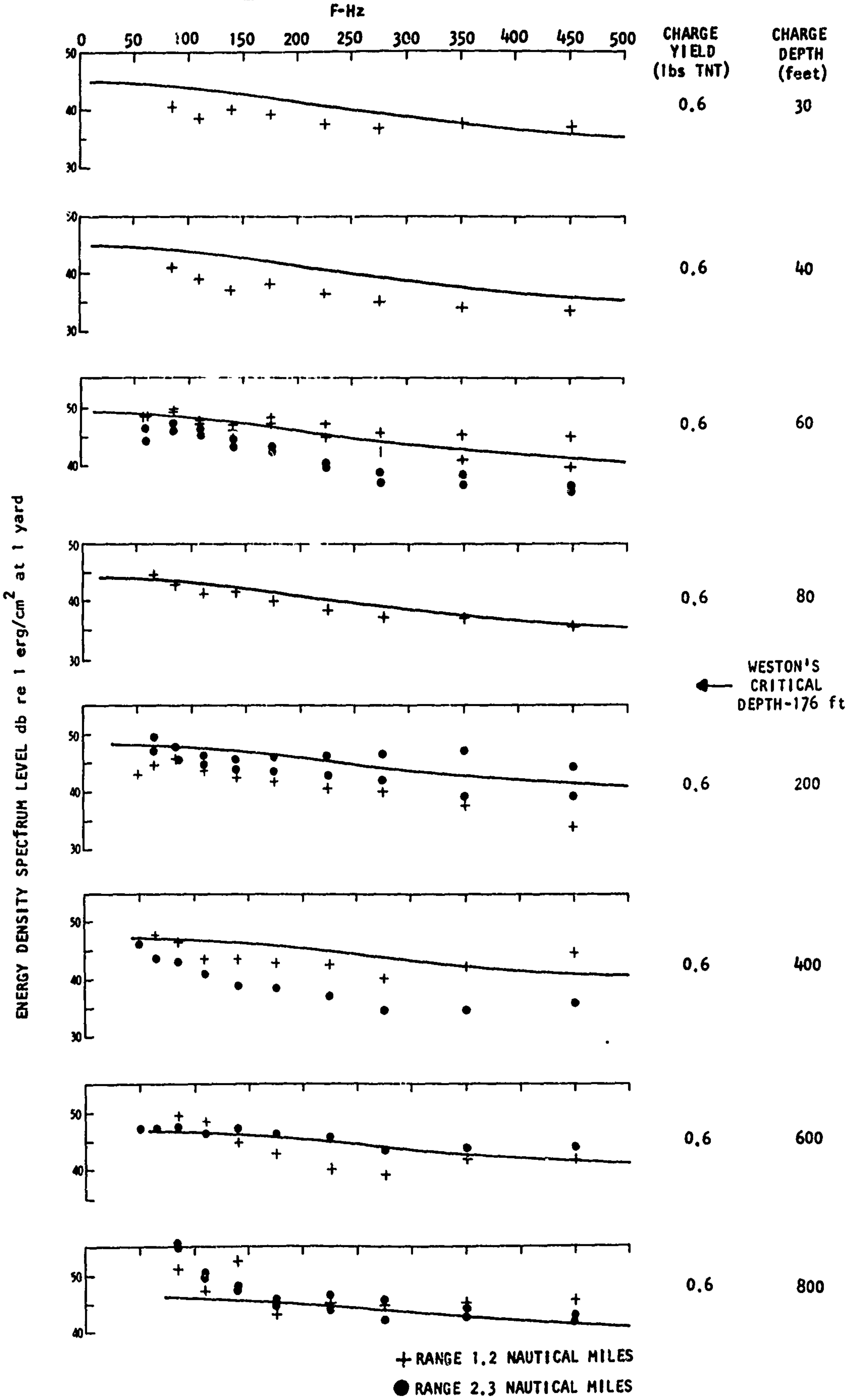

Figure 6. Measured Source Level and Weston's Predicted Source Level

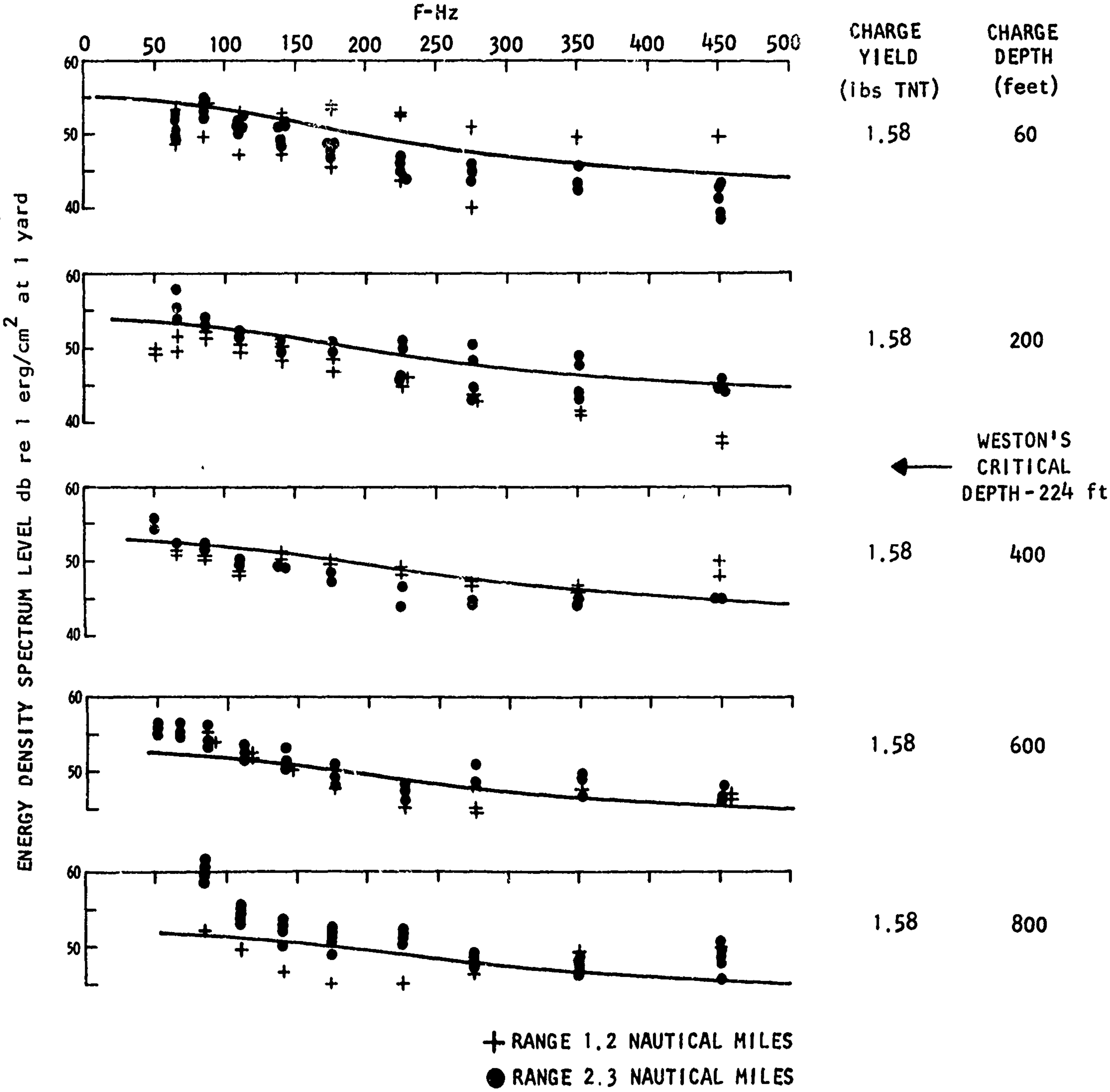

Figure 7. Measured Source Level and Weston's Predicted Source Level

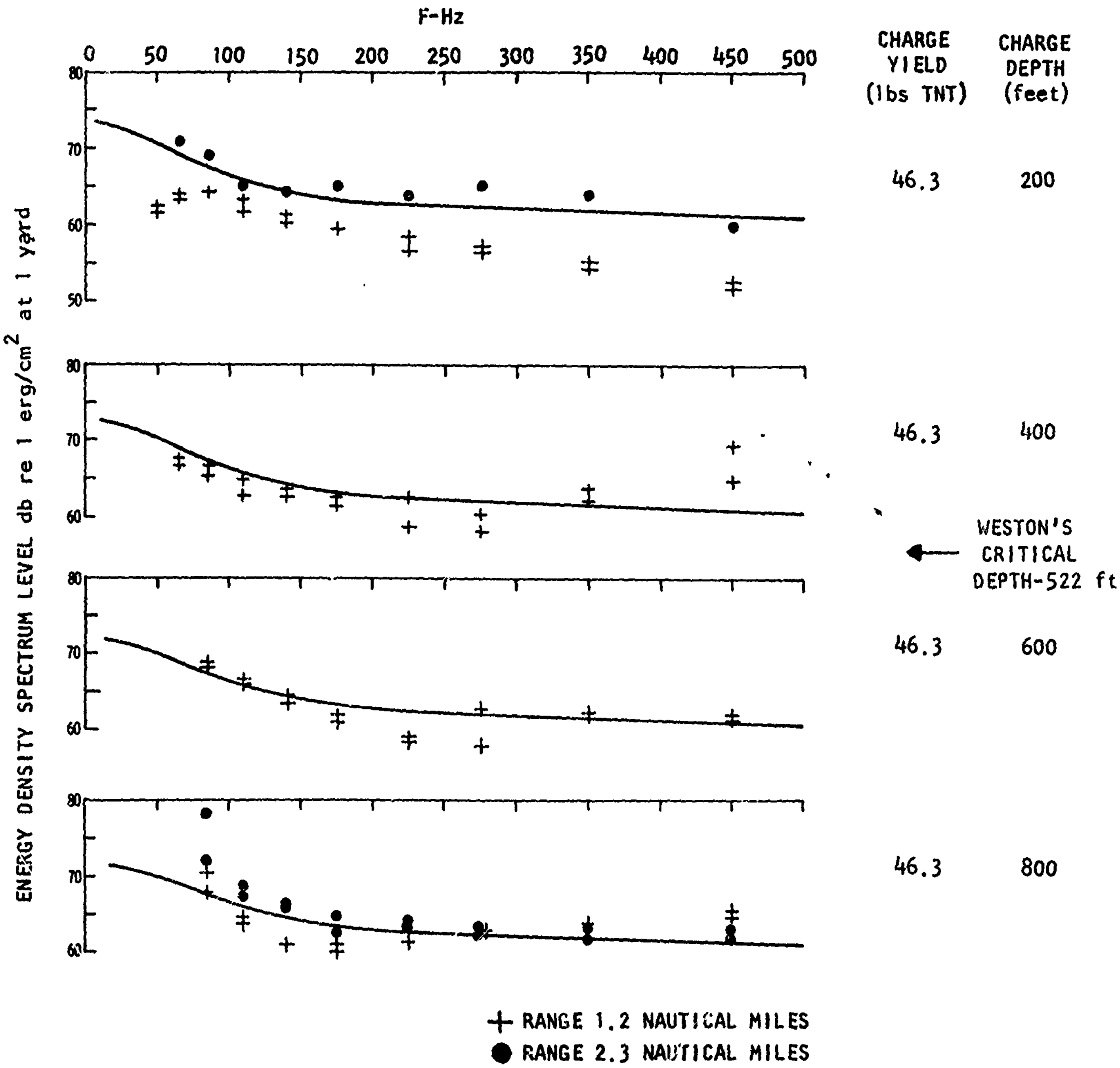

Figure 8. Measured Source Level and Weston's Predicted Source Level

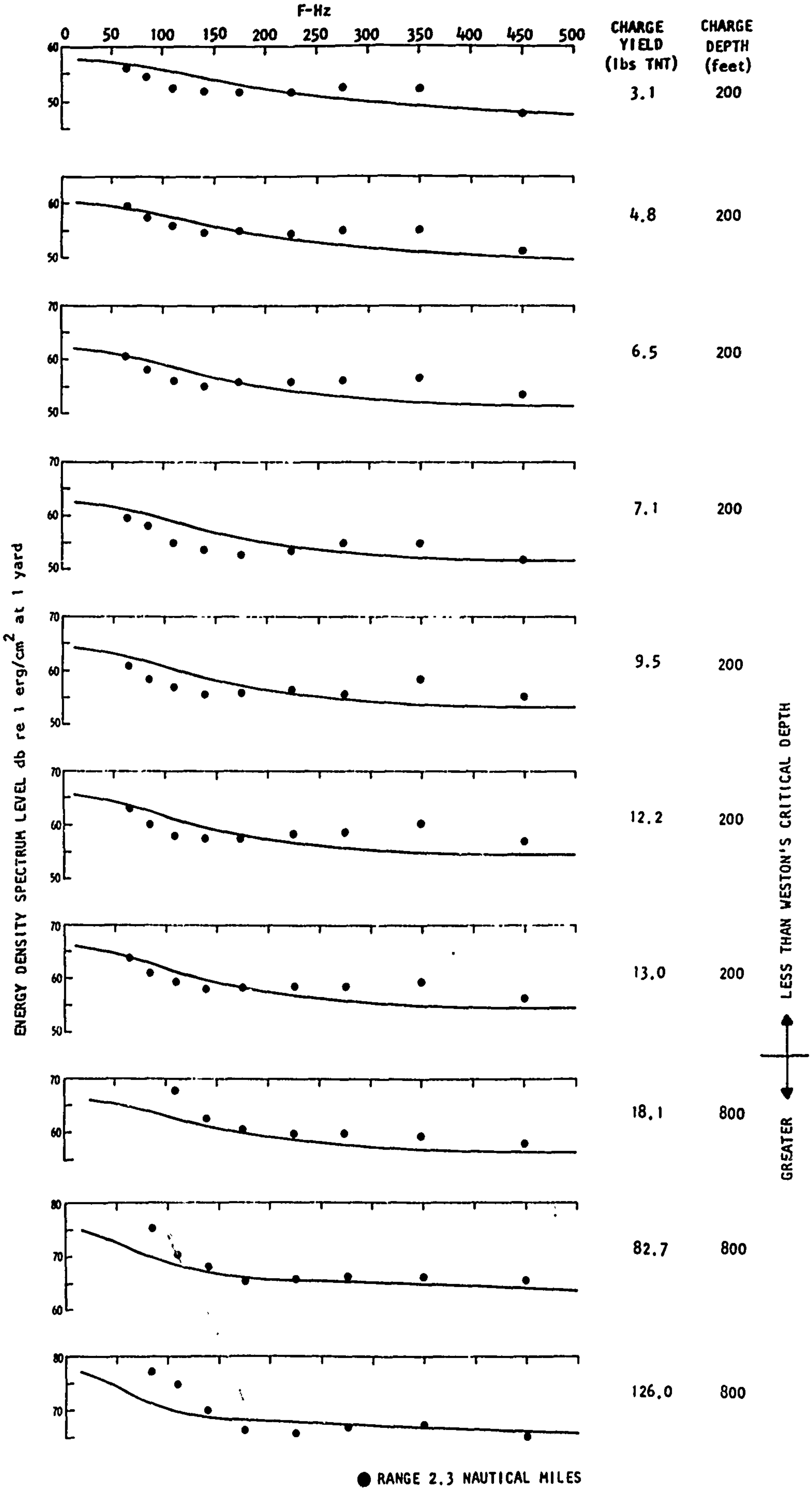

Figure 9. Measured Source Level and Weston's Predicted Source Level

propagation paths where there are only a few dominant multipaths and can be caused by slight motions of the projector and hydrophone. Since the explosive signal gave an instantaneous "picture" of the propagation conditions that obtained for only a fraction of a second, the differences between predicted and measured energy source levels could be expected to vary considerably. Therefore, it is not only permissible but necessary to average the data to derive a true comparison.

Figure 10 is a compilation of all shots at both ranges giving average and standard deviation differences between Weston's predictions and measurements of energy source level. The agreement is strikingly good. If the results of Figure 10 are further averaged (over frequency), the result is that the measured energies are only 0.2 dB lower than Weston's predictions.

ENERGY SOURCE LEVELS BELOW THE FIRST BUBBLE PULSE FREQUENCY

Having established, within the accuracy limits imposed by the CW measurements, that Weston's sum formula is a close representation of the true energy source level of an explosive above a frequency equal to about the first bubble pulse frequency, source levels below that frequency were determined in the following manner. MK14 charges (nominal yield 50 pounds of TNT, although measurements indicated an average of 46 pounds) detonated at various depths at ARLIS 6 and received at ARLIS 5 at an average distance of 133 nautical miles were used to determine transmission loss assuming Weston's sum for source energies. Only those frequencies above the first bubble pulse frequency for the MK14 were used. Each MK14 shot at a particular

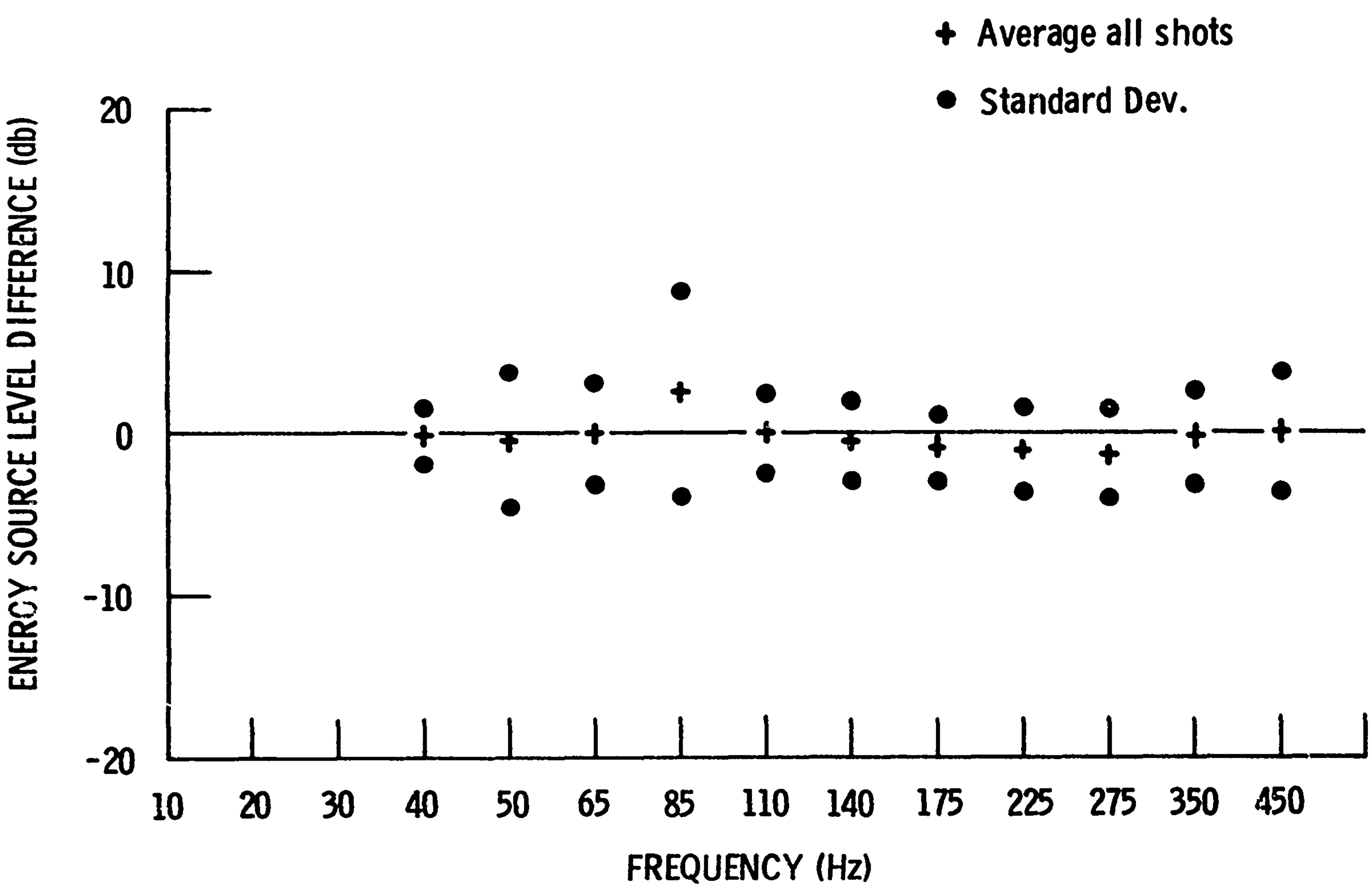

Figure 10. Measured Minus Weston's Sum Energy Source Levels vs Frequency for All Shots

depth was closely followed by a MK61 shot (nominal yield 1.8 pounds of TNT but measurements indicated an average of 1.6 pounds). The received energy flux density of the MK61 measured at discrete frequencies below its first bubble pulse frequency was increased by the corresponding transmission loss to compute the source level. The results were normalized relative to the source level at the first bubble pulse frequency and are plotted in Figure 11 for shot depths of 200, 400, 600 and 800 feet. Superimposed on the log scale is a best-fit straight line through the origin, which is at +7 dB/octave.

CONCLUSIONS

Weston's sum prediction source level as a function of yield and depth is correct at frequencies above the first bubble pulse frequency, when used with reception bands wide enough to encompass multiple (at least three) first bubble pulse harmonics, and can be used with confidence when explosives in the yield range 0.0012 to 126 pounds TNT are employed to determine transmission loss, providing that a statistically sufficient number of charges are used to describe fluctuations. The range at which explosive energy travels as an acoustic wave, as predicted by Arons and Plutchok, apparently has no bearing on Weston's prediction of source level in the determination of transmission loss.

Within the limits of the experiment, there appear to be no significant bubble migration effects in energy. Therefore, Weston's critical depth formula is considered highly conservative and considerably shallower shots can be used in transmission loss measurements.

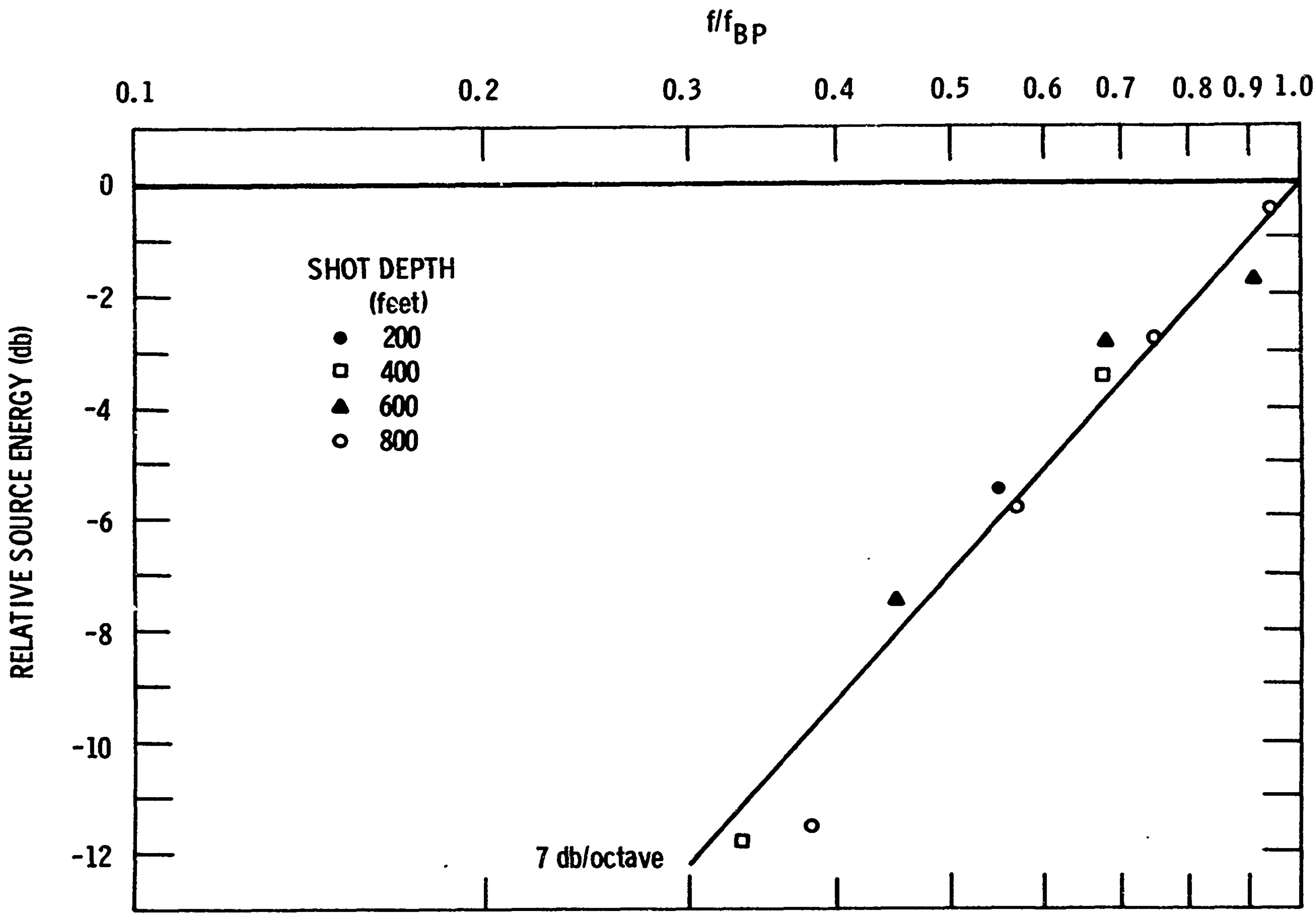

Figure 11. Measured Relative Source Level Energy Below First Bubble Pulse Frequency

At frequencies below the first bubble pulse frequency, energy source levels for explosives can be approximated by a 7 dB/octave increase with frequency.

ACKNOWLEDGMENT

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